Naval Research Laboratory

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NRL Memorandum Report 6874

Plasticity in Shocked Single Crystals Viewed by Pulsed X-Ray Diffraction

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October 5, 1991

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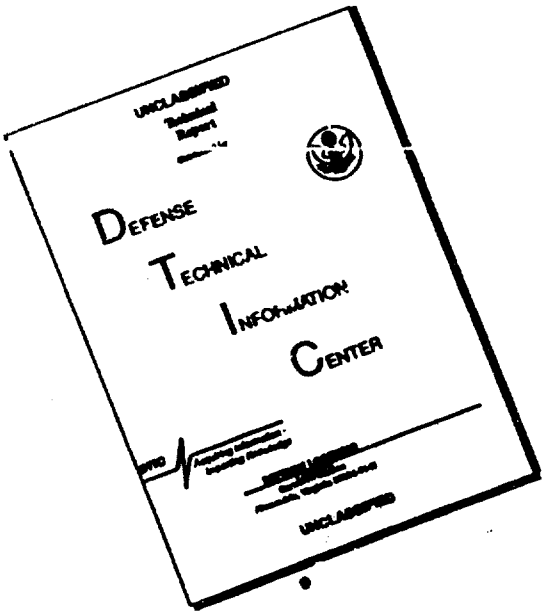

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	1991 October 5	NRL Memorandum Report

4. TITLE AND SUBTITLE
Plasticity in Shocked Single Crystals Viewed by Pulsed X-ray Diffraction

5. FUNDING NUMBERS
46-2883-I-1

6. AUTHOR(S)
Robert R. Whitlock and Justin S. Wark*

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Washington, DC 20375-5000

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL Memorandum Report 6874

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
800 North Quincy Street, BCT #1
Arlington, VA 22217-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
*Current address: Clarendon Laboratory, Parks Road, University of Oxford Oxford OX1 3PU UNITED KINGDOM

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

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14. SUBJECT TERMS
X-Ray, Laser-Produced Plasma, Diffraction, Plasticity, Lithium Fluoride, Shock

15. NUMBER OF PAGES
8

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNLIMITED

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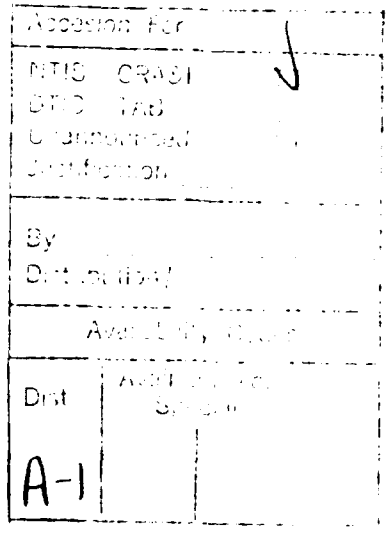

PLASTICITY IN SHOCKED SINGLE CRYSTALS VIEWED BY PULSED X-RAY DIFFRACTION

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X-ray diffraction from single LiF crystals was performed parallel (Bragg orientation) and transverse (Laue orientation) to shock fronts generated by nanosecond laser pulses. Subgrain boundaries are noticeably affected by the shock. Transverse elastic strain with both tensile and compressive components is seen. These novel observations are interpreted as evidence of dislocation motion and the onset of plasticity.

1. INTRODUCTION

The generation of transient events with high power, multiple beam lasers offers excellent synchronism between beams. With one beam used to drive a shock and another beam tightly focused to produce a plasma x-ray source (see Figure 1), the lattice spacing of shocked single crystals may be measured with temporal resolution well below a nanosecond, as we have demonstrated in previous work.[1,2] In this paper, we further establish the utility of the method in examining lattice planes not parallel to the surface (in the present case, orthogonal to the shock front), and exhibit the ability to perform time resolved spatial imaging of microstructural events.

2. EXPERIMENTAL

In order to observe plastic deformation, we chose LiF, which has a low HEL and is readily available in single crystal form. Much work has been done on the shock response of LiF (for example,[3,4,5,6]) and the difficulty involved in obtaining reproducible and reliable results with soft, annealed samples is well known. Our samples were gamma ray hardened LiF from Harshaw which were cut into sections and carefully polished at the Clarendon Laboratory to about 80μm thickness, coated with aluminum to absorb the laser and generate the shock, and then coated with a plastic tamper at the Rutherford Appleton Laboratory. The final samples, about 7x10mm in size, were irradiated individually by a few J/cm^2 of 1ns, λ=1.06μm light from the Janus Research Laser at the Lawrence Livermore National Laboratory. The Ti x-ray source was about 50μm in diameter, formed at the focus of a frequency doubled laser beam the duration of which varied (0.1-1ns) during the experimental series.

X rays from the source were diffracted from two sets of planes in the crystal simultaneously. The first was the usual planes parallel to the crystal surface, i.e., typical Bragg diffraction geometry. The second set

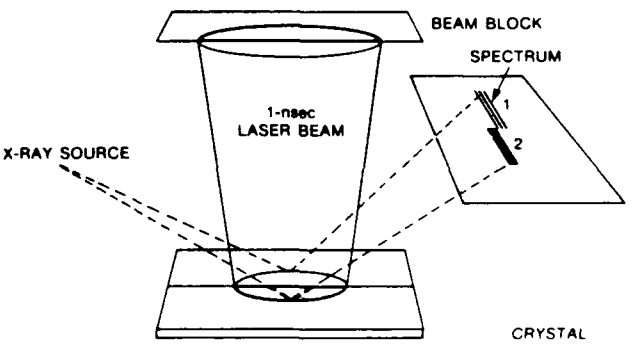

FIGURE 1
Experimental arrangement, Bragg geometry.

Manuscript approved August 5, 1991

was orthogonal to the surface, which we shall refer to as Laue geometry; these diffracted rays passed completely through the crystal. The 1/e x-ray penetration depth in LiF is about equal to the thickness of the crystal, a distance much greater than the propagation of the shock during the event. The signal levels for shocked crystal volumes are aided by the large factor by which plastic strain enhances reflectivity above that of single crystal, "perfect" LiF.[7]

3. SUBGRAIN BOUNDARY IMAGES

The point source, flat crystal geometry affords one dimension of spatial resolution along the arc of diffraction. Our x-ray source has a suit of closely spaced lines which form self similar arcs on the film if the crystal is truly flat. Each line serves to image a segment of the crystal surface, much like a raster scan in a CRT. As the Bragg angle changes under shock conditions, additional portions of the crystal surface can come into view.

The slight angular displacement at a subgrain boundary can cast the diffraction from neighboring sides of the boundary onto the film with an overlap, a separation, or, as in Figure 2, a complete displacement in the diffraction lines. The displaced, distinct lines are from the subgrain at a depth sufficient to have remained unshocked. The diffraction from the compressed single crystal matrix and subgrain are seen below the distinct matrix lines. It should be noticed that the offset between the shocked subgrain and the shocked main crystal appears less than for the unshocked signatures.

A larger subgrain, sufficiently large to see both sides well removed from each other, was also shocked, one side of which is shown as Figure 3. Here also, the subgrain boundary appears to merge with the surrounding crystal when shocked. This appearance is substantiated by densitometric scans through and adjacent to each subgrain boundary. Under shock loading, the boundary on one side of the subgrain increases in reflectivity while the other decreases; both merge with their surroundings.

Subgrain boundaries may be represented as collections of dislocations at an angular disjuncture of lattice planes. Images such as that in Figure 3 demonstrate the diminution of this angular mismatch. From the delocalization of the diffraction signature of the subgrain boundary, we infer the delocalization of the dislocation population in response to the shock.

The role of subgrain boundaries, as sources of mobile dislocations important to the shock response of soft LiF (at lower stresses and with a different driver), has been stressed Meir and Clifton,[6] similar insights having been expressed by Vorthman and Duvall.[5]

FIGURE 2
Image of a subgrain, unshocked (distinct; short lines are from subgrain) and shocked (blended band)

FIGURE 3
Image of one side of larger subgrain (gap in the x-ray lines). Gap closes under compression.

4. TRANSVERSE STRAIN

Elastic uniaxial compression is accomplished in the absence of transverse strain. That is, neighboring volumes under a constant elevated stress will inertially confine each other and prevent displacements in directions orthogonal to the shock propagation direction. Until sufficient time has elapsed for lateral release waves to arrive from the boundaries of the sample (causing a departure from uniaxial conditions), the total transverse strain must remain zero. Should this lateral inertial confinement break down, e.g. by local plastic deformation, then local transverse strains will result from the imposed stresses, but the total of such strains, whether elastic or plastic, must still remain zero. In the hydrostatic limit (isotropic stress, zero shear), compression in orthogonal but crystallographically equivalent directions will be essentially identical. Thus, by measuring the lattice compression parallel and perpendicular to the shock in the cubic crystal LiF, we expect to be able to measure the dimensionality of the compression. Quintin Johnson, et al., have made x-ray diffraction measurements (of duration 10's of ns, much longer than ours) and concluded that LiF lattice spacings parallel to shocks of known strength are consistent with an expected isotropic volume compression in powder targets[8,9] and in single crystal targets,[9,10] and that single crystal LiF is not immediately commuted to powder.[10] On the other hand, similar experiments on single LiF crystals by Kondo, et al., demonstrate the anticipated shock-induced angular spreading such as is present in mosaicity or outright comminution.[11]

It must be borne in mind that x-ray diffraction is a consequence of an ordered lattice, and therefore is a probe of the elastic response of a material. Atomic orientations which are sufficiently at variance with the lattice, e.g. due to plastic deformation, will only be detected insofar as they influence the remaining ordered lattice. In the effectively infinite transverse direction, the requirement of zero total strain equates the elastic strain (which is directly measurable) to minus the plastic strain (which may then be inferred).

Obviously, a single crystal several mm in size cannot convert a uniaxial compression into an elastic isotropic compression in the few nanoseconds available for sound propagation. We therefore expect to see the dimensionality change from one to three on time scales not to exceed those of Johnson and Kondo, and we further expect this to take place plastically. (Due to the presence of a degree of laser beam nonuniformities, our shocks are not purely one dimensional.)

We have taken simultaneous, orthogonal diffraction images of LiF and do indeed see transverse strain. We find that the strain signatures in the two directions are not necessarily identical. In fact, we have repeatedly measured both compression and tension transverse to the shock (Laue direction), both tension and compression occurring within unresolvable proximity to one another and while the sample is still under compression (as seen in the Bragg direction). See Figure 4. The actual lattice behavior in this strain dimensionality transition is therefore more complex than either the uniaxial or the hydrostatic limits. Possible sources of tensile/compressive signatures include dislocations, rotations, and fractures.

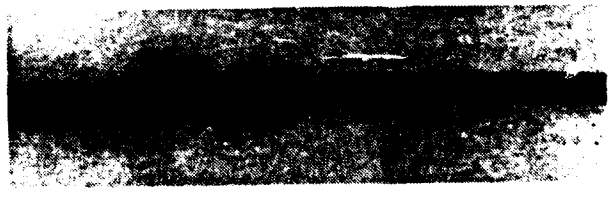

FIGURE 4
Laue image with mild compression and tension. Stronger effects have been recorded on other films.

5. CONCLUSIONS

We have seen striking signatures of the developing stages of plasticity in laser shocked LiF. Some of these signatures pertain to identifiable microstructures, i.e., subgrain boundaries. Improvements in the uniformity of synchronizable shocks would be expected to yield corresponding advances in our ability to resolve lattice level phenomena.

6. ACKNOWLEDGEMENTS

We express our appreciation to V.W. Slivinsky for laser scheduling, to James Swain and his staff for laser operations, and to the staffs of the Clarendon Laboratory and the Rutherford-Appleton Laboratory for assistance with target preparation.

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